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HARDWARE METAPAPER

CubeFactory2 – an Off-Grid and Circular 3D-Printing Mini-Factory

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The CubeFactory2 is a self-sufficient and luggage-sized production unit illustrating the concept of sustainable manufacturing through circularity and resource conservation. It is circular in the sense that it can create new products out of waste. It embeds a Fuse Filament Fabrication 3D-printer whose input material is supplied by a recycling unit producing filament out of thermoplastic waste. It saves resources in the sense that it embeds renewable energy and material supply to recycle and 3D-print without the need for further infrastructure. In its current state of development, the purpose of the CubeFactory2 is primarily illustrative and to support awareness on sustainable manufacturing. If offers an experienceable application of the concepts of circularity and resource conservation. The long term vision is to take advantage of its compactness, portability and autonomy, in order to enable fabrication in areas of low infrastructure.

The CubeFactory2 combines off-the-shelf and custom subsystems, the four mains of which are a 3D-printer, a recycler, an energy supply unit, and a casing. The present hardware meta-paper describes the design rationale of these systems and offers complementary information to the published open source hardware design files. Great care has been paid in the design process to enable replicability by using standard components when possible and releasing all documentation of bespoke elements following open source standards. This article should contribute to make this functional proof of concept ready for replication and for further development towards a market-ready product.

Keywords: mini-factory; circular economy; filament recycling; 3D-printer; making; sustainable manufacturing

Metadata Overview

- Main design files: https://github.com/CubeFactory2/cubefactory.
- Target group: For replicating the CubeFactory2: school or academic staff, engineering and technical staff of charity associations, NGOs and scientific staff. For using the CubeFactory2: secondary school students, layperson, and undergraduate students.
- Skills required for building the device: 3D printing – easy; mechanical assembly – easy; electrical assembly – advanced; machining – specialist; electricity – specialist.
- Replication: No builds known to the authors so far.

(1) Overview

Introduction

Raising awareness on the concept of sustainability and its relation with manufacturing is a critical issue on the path to a sustainable society. In spite of considerable media echo given to the concept of sustainable development, it remains difficult for the general public to link it to manufacturing activities (Roeder et al. 2016). "Sustainability" and "manufacturing" remain for a large part of the population terms they may have heard of but never really got explained – and this despite the central role these concepts play in today's debates on the direction to take to reach durable welfare (Stark et al. 2016).

Desktop 3D printing is one of the recent technological advances that allow downsizing manufacturing activities and relocating them away from factories and back in the hands of the individual citizen. 3D printers and the "making" activities they support are good points of contact to help individual people experiencing fabrication activities and reflecting on resource use. This is supported by a context of growing preoccupation about plastic waste in the public debate. While 3D printing can be considered as socially beneficial in the sense that it empowers individual action, it also reduces the costs of creating objects of low value and encourages try-and-error design processes producing misprints (Klemichen et al. 2018). The maker communities and markets reacted to this context and developed plastic filament recyclers as part of the solution to cope with plastic waste. Noteworthy examples of

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open source recycling devices are the Precious Plastics' Extrusion Machine[1] or Felfil[2].

Nonetheless, filament recyclers have only been developed as freestanding machines so far. The CubeFactory2 introduced in this article packages 3D printing and filament recycling technologies in a single off-grid and portable unit (see **Figure 1**). It combines (1) an open source recycler producing 3D-printer filament out of plastic waste, (2) a self-sustaining energy supply unit in the form of photovoltaic panels with batteries, and (3) an open source 3D-printer implementing the Fuse Filament Fabrication (FFF) process (see **Figure 2**). These elements are embedded in a robust flight case of the size of a large travel suitcase, with a total weight less than 32 kg. The autonomy and portability of this implementation of the concept of mini-factories (Postawa et al. 2009) makes it in particular relevant for applications in awareness raising actions as well as value creation in areas of low infrastructure. This

Figure 1: The CubeFactory2.

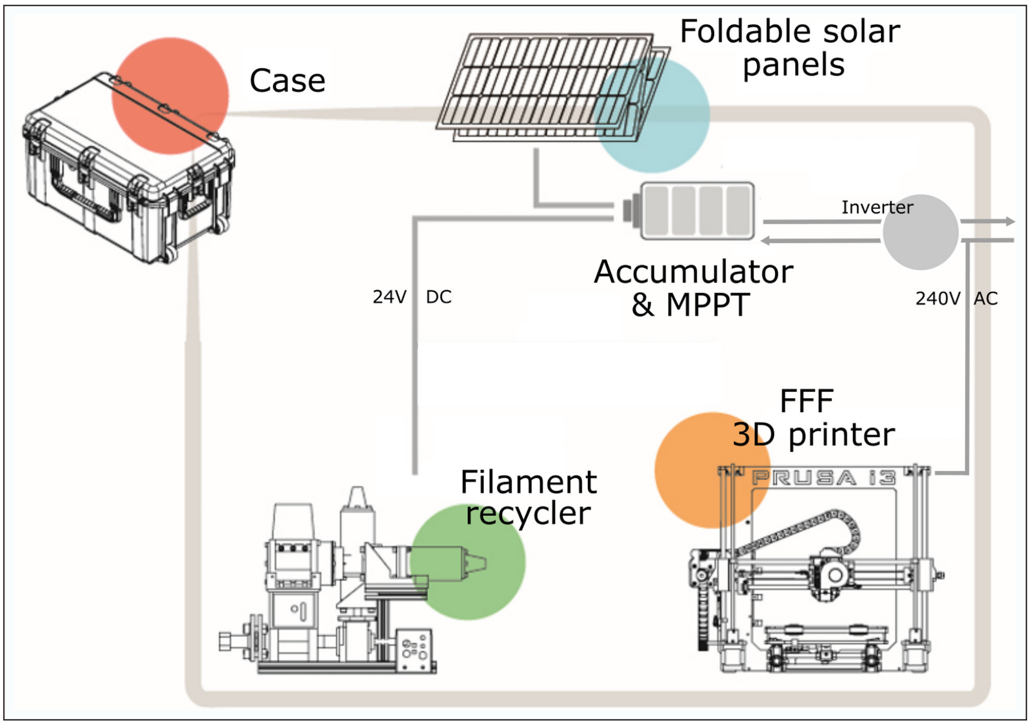

Figure 2: Schematic representation of the CubeFactory2's subsystems. (MPPT stands for Maximum Power Point Tracking and FFF stands for Fuse Filament Fabrication).

device exemplifies the concept of sustainable manufacturing through circularity and resource conservation. It is circular in the sense that it enables closed-loop material cycles by creating input material for the creation of new products out of plastic waste. Resource conservation is exemplified through the autonomy provided by solar panels and the resource-saving potentials of additive manufacturing processes. Compared to many conventional manufacturing processes that mill, cast or shape objects from solid material, additive manufacturing enables the fabrication of lightweight structures and shortens process and supply chains. In addition, 3D printers are a suitable tool for the production of spare parts.

The device described here is a complete redesign of a proof of concept first introduced in Muschard and Seliger (2015). All subsystems have been redesigned to reduce the occupied volume and to gain in mobility. The volume has been divided by six—version 1 occupying one cubic meter and version 2 measuring 80 × 40 × 52 cm being approximately one sixth of a cubic meter. The CubeFactory2 is described in a consistent documentation released under open source terms and deposited in a publicly accessible online repository. It is therewith open for replication and further improvement by any interested person.

The device is a combination of off-the-shelf and self-developed subsystems. **Table 1** summarizes which of the subsystems are original developments or off-the-shelf components and which of them are open source or proprietary. All original developments have been documented sufficiently to ensure the four freedoms of open source (Bonvoisin et al. 2017) and have been released with a license compatible with the requirements of the OSI (Open Source Initiative)[3]. Therewith, the CubeFactory2 is compatible with the certification criteria of the Open Source Hardware Association.[4] In this document, off-the-shelf components are clearly identified as such. Appropriate references and specifications of these components are given in the full documentation, either in the text or in the bill of materials.

Overall Implementation and Design

The CubeFactory2 is composed of four subsystems described separately in the following subsections. The recycler aims at producing FFF-ready filament out of sorted thermoplastic waste, typically ABS casings, PET bottles or PLA 3D printing misfits. The 3D-printer fulfils the main function of the CubeFactory2, that is, to produce 3D-objects printed by Fuse Filament Fabrication. Both, the recycler and the 3D-printer are driven by the energy supply subsystem and are enclosed in the flight case which both contribute to the autonomy and the portability of the overall system. For the casing, a standard flight case made of impact-resistant as well as lightweight plastic was used. It includes a storage space for the optional inclusion of a tablet PC or laptop to operate pre-printing operations.

Recycler

The plastic recycler is an in-house development belonging to a series of prototypes built by the authors, next to the Home Recycling Device (Zwier 2012) and the RecycleBin.[5] The function of the recycler is to produce 3D-printing-ready filament out of sorted thermoplastic waste, i.e. misprints or other post-use waste products. An overview of this subsystem is delivered by **Figures 3** and **4**.

The recycler performs two process steps: granulation and extrusion. Input material is first granulated by a mechanical shredder (a) into small chips which are fed through gravity into a hopper (b) at the entrance of the screw extruder. The shredder is made of a reused post-use milling tool rotating in a cylindrical chamber designed to fit the dimensions of the tool. It produces small chips as displayed in **Figure 5**. In the extruder, chips are compressed and conveyed by a spinning worm screw towards an extrusion nozzle. After passing a thermal barrier preventing the chips to melt prematurely (c), the compressed chips are fed into the extrusion nozzle (d) which is heated by an off-the-shelf sleeve heater (e). Under both heat and pressure, the chips melt and are pressed out through the nozzle, hence producing ready-to-use filament.

Both, the shredder and the extruder are driven alternatively by a shared powertrain which has to be switched manually between two positions (f and g). This implies that the recycler can only alternatively shred material or extrude it. This solution has been chosen in order to reduce component redundancy and therewith to increase compactness, as well as to reduce energy peaks, fabrication cost, and machine weight. The main components of the powertrain are a brushless DC motor (h), a planetary gear (i) and a motor controller (not displayed on the drawing). The DC motor has been dimensioned in order to get the sufficient torque to shear and cut parts made of ABS, PET and PLA, which are the typical materials addressed. The planetary gear operates a reduction of 10:1 in order to increase the torque, lower the speed and reduce the shear strength of the processed material. An off-the-shelf motor controller is used to put the brushless motor in motion and allows the user to vary the motor speed by means of an analogous potentiometer.

Table 1: Source and licensing scheme of the four main subsystems of the CubeFactory2.

Subsystem	Sourcing	Licensing
3D-Printer	Off-the shelf (Reprap Prusa i3 Hephestos)	Open source (CC-BY-SA 4.0)
Recycler	Own development	Open source (CC-BY-SA 4.0)
Energy Supply	Composite of bespoke and off-the-shelf solutions	Components are proprietary, wiring is open source (CC-BY-SA 4.0)
Casing	Off-the-shelf	Proprietary

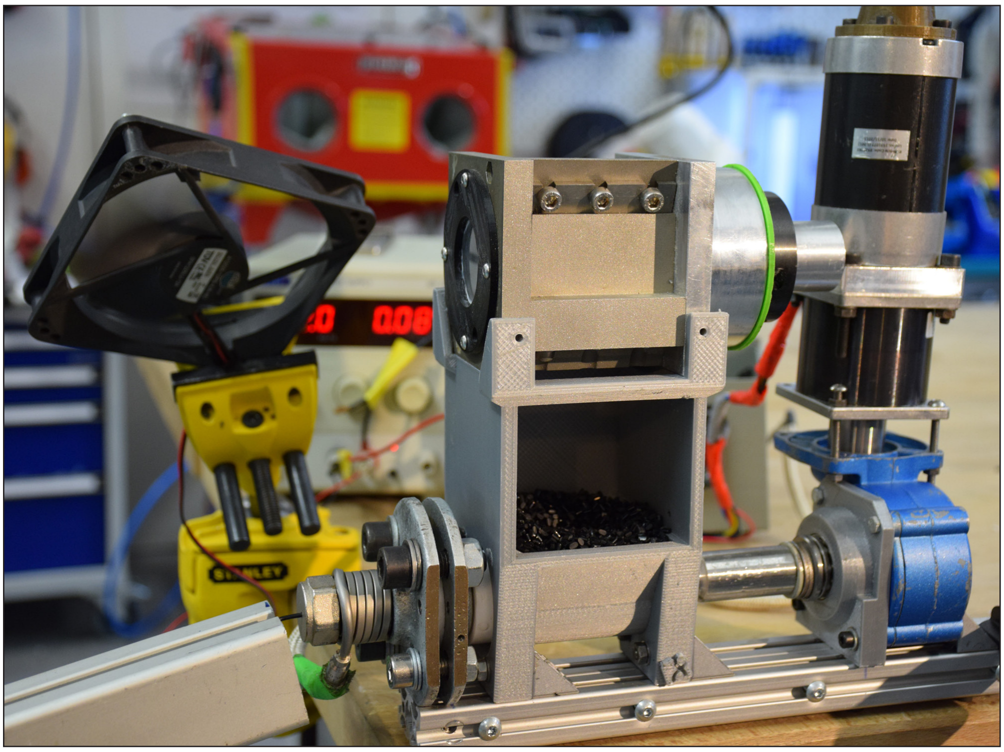

Figure 3: Recycler, rear view (the fan, its mounting and the filament trap are not part of the device).

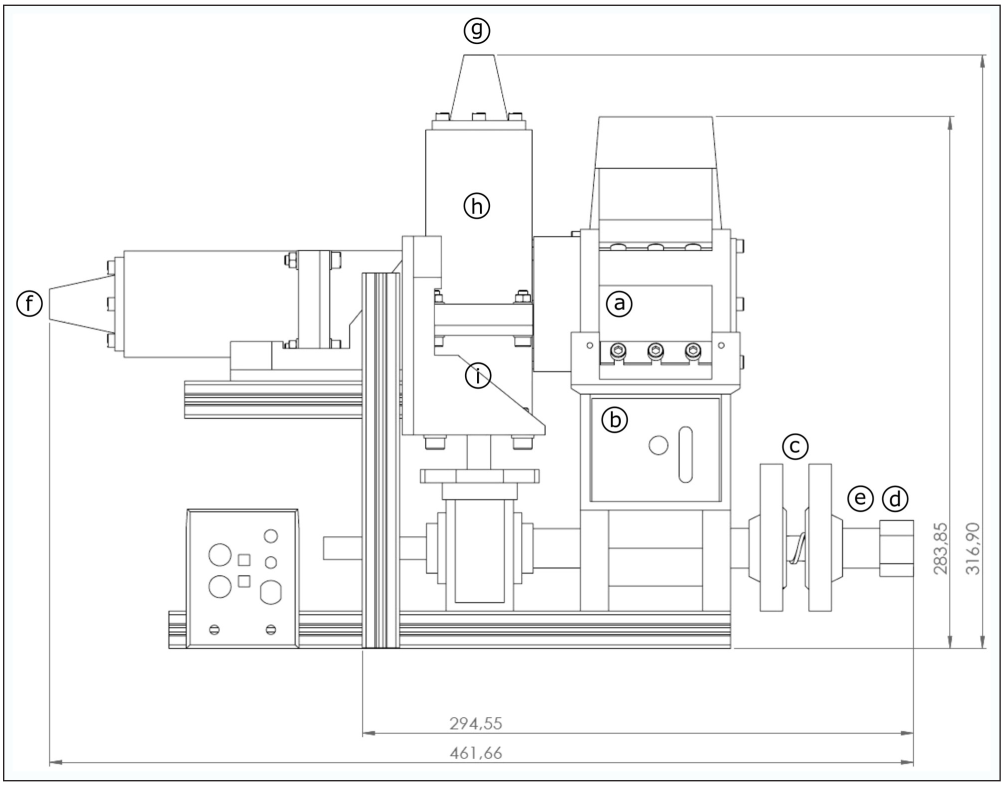

Figure 4: Mechanical drawing of the recycler (dimensions in mm), front view.

The extrusion process can be adapted depending on the material by adjusting the heating temperature and the rotating speed of the worm screw. The heating temperature can be adjusted and maintained over time with the help of an in-built temperature controller (also off-the-shelf). The sleeve heater is dimensioned to reach a maximum temperature of 250°C, which has been deemed as high enough to process the targeted plastic types. Nozzles can be swapped in order to produce either ø1.75 mm or ø2.85 mm filament. The electrical wiring of the thermic and mechanical elements of the recycler is reproduced in **Figure 6**.

Figure 5: Plastic chips produced by the shredder (PET from “Muellermilch” bottles and mixed other objects).

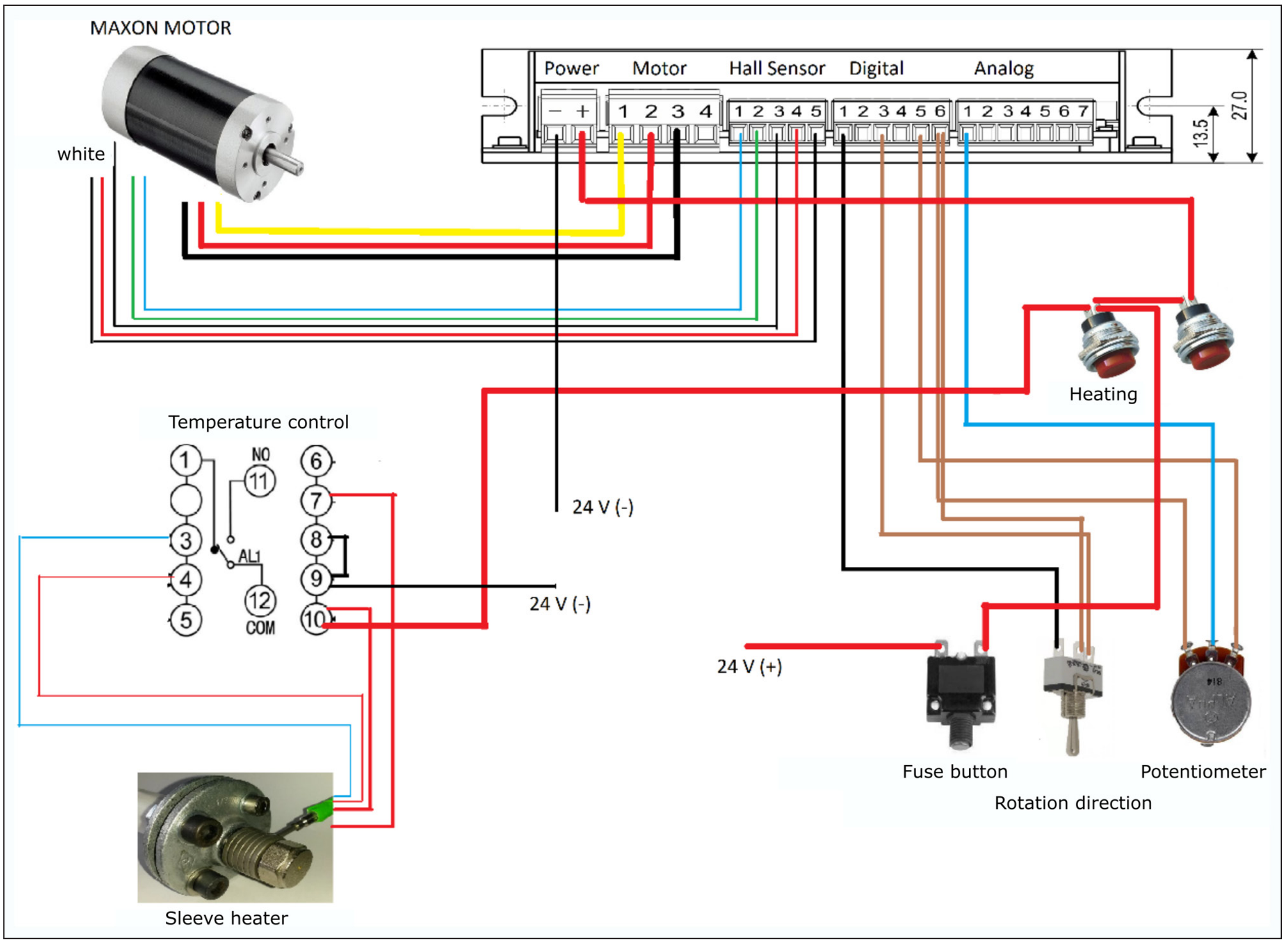

Figure 6: Electrical wiring of the recycler.

Energy supply

Electrical power is provided by photovoltaic (PV) modules and a battery storage system managed by a MPPT charge controller (Maximum Power Point Tracking). These are either bespoke or off-the-shelf components, so only their combination and wiring is reproduced here. Attention has been paid to use components that are commonly available on the market, however, individual components were adapted to specific requirements. For example, the solar modules have bespoke dimensions in order to make maximum use of the available storage space in the casing.

The PV modules convert sunlight directly into electrical direct current, allow to operate the energy-using subsystems and to charge the battery storage system. The PV modules themselves consist of three bespoke foldable Si-mono modules fitting the dimensions of the flight case once folded. Altogether, unfolded, the three modules reach a surface of approximately three square meters[6] and have a cumulated nominal output power of (145W per module). The function of the battery storage system is to store the energy surplus generated by the PV modules, to compensate the irregular voltage and current generated by the PV modules, and to enable 3D printing in absence of direct daylight. It is implemented by a $LiFePO_4$ battery with an operating voltage of 12V and a storage capacity of 1.28 kWh. The MPPT charge controller ensures the operation of optimal charge and discharge parameters in order to preserve the battery as far as possible. It balances the difference in nominal voltage of the battery and the PV modules and continuously computes the optimum operating point in terms of input and output power. The electrical wiring of the three components contributing to energy supply of the CubeFactory2 is reproduced in **Figure 7**.

While the operating voltage of the battery is 12V, electrical energy is supplied to the recycler at 24V DC in order to reduce the electrical current and associated hazards. While the 3D printer runs on 12V DC and would not need any current transformation, it is wired through an in-built 240V AC to 12V DC transformer. We made the choice not to modify the off-the-shelf printer (see section "3D-printer") and to provide it with 240V AC produced by an AC/DC inverter transforming 12V DC from the battery. Alternatively, the in-built 240V AC to 12V DC converter could be bypassed to feed the printer directly with DC from the battery without any conversion, hence yielding a higher energy efficiency.

The battery has been dimensioned to offer at least one day of operation without any input of solar energy. The power consumption of the 3D-printer is 80W at 12V without heating bed and 150W at 12V with heating bed. The battery provides enough energy to power the 3D-printer for around six hours with a heating bed and 12 hours without at 80% maximum battery discharge. The maximal power consumption of the recycler's motor is 240W at 24V. The maximal energy consumption of the sleeve heater is 150W at 24V. Assuming that the recycler would constantly operate at its maximal consumption, the battery would provide enough energy to power the recycler 4 hours, i.e. enough to produce material for several days of 3D printing. However, the motor may only reach its maximal power consumption in shredder position, so the autonomy while recycling may be longer. Its actual consumption in extrusion position is significantly reduced by the planetary gear. The heating sleeve is thermally well isolated, only operate at maximum power at the beginning of a recycling job and consumes less energy after pre-heating. The nominal output power of the solar panels is significantly above the value required to power the 3D-printer or the recycler indefinitely.

The dimensioning of the power systems suppose an alternated use of the 3D printer or the recycler. Assuming a linear charging profile of the battery and good sunlight conditions, the battery can be charged within a day.

3D-Printer

The CubeFactory2 embeds the 3D-printer Hephestos, which is a derivate development of the RepRap Prusa i3 (see section "Dependencies" for more precise attributions). This printer has been chosen based on price/performance ratio, energy efficiency, compactness and weight. In spite of its compactness, the maximal printing dimensions are 215 × 210 × 180 mm, which amounts to a volume of approx. 8 litres. The Prusa i3 Hephestos is open source and is supported by a large community of users and developers. Spare parts are openly available and can easily be reprinted. No substantial modifications have been made to this original off-the-shelf and open source hardware in order to fit it in the CubeFactory2.

Flight case

The production-relevant subsystems of the CubeFactory2 are enclosed in a 0.17 m^3 portable flight case equipped with handles and wheels for ease of transportation (off-the-shelf component, proprietary). To meet the requirements for the lowest possible weight, a housing made of lightweight but impact-resistant plastic was chosen. The subsystems have been screwed directly into the structure

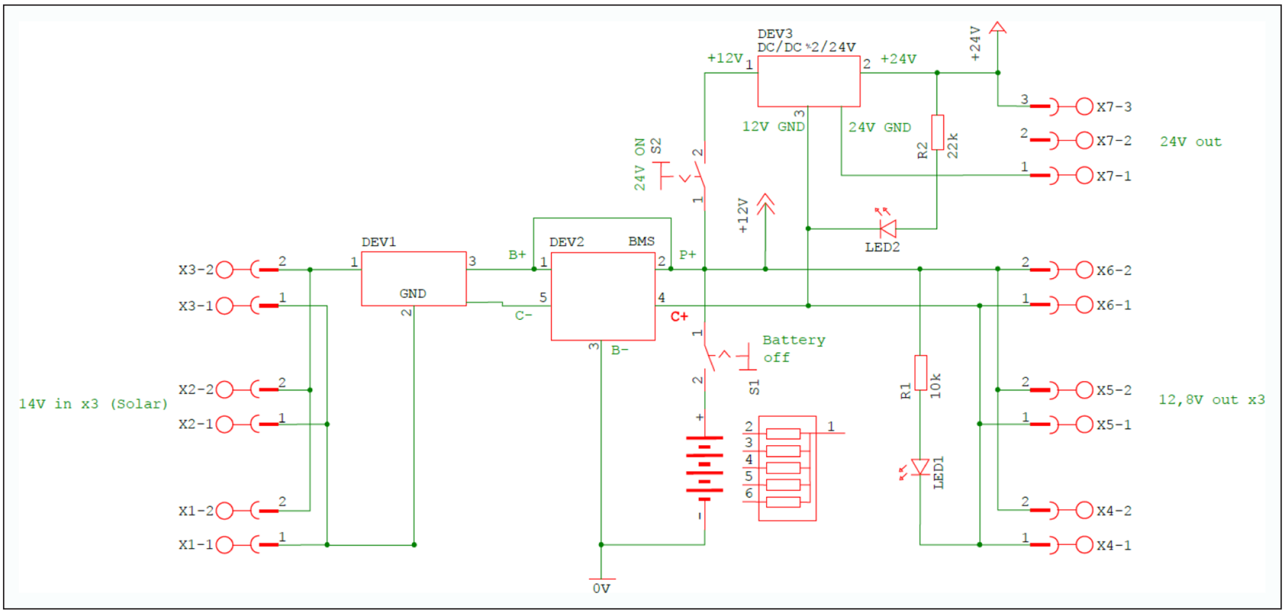

Figure 7: Electrical wiring of the energy supply subsystem.

of the originally IP76-rated case, lowering its performance to IP65 (protection against dust and water jets, own estimation, not tested in lab conditions). The CubeFactory2 can either be operated open or with closed lid to protect the enclosed systems from rain and dust.

(2) Quality control

Safety

Four sources of safety issues have to be considered: electrical power, sharp moving parts, gaseous emissions, and heating elements.

Risk of electrical shock should be considered while assembling and servicing the battery. While the voltage of the battery (12V) may not be high enough to break the impedance of human skin, particular attention has to be paid while assembling and servicing the inverter providing the 3D-printer with 240V AC. All electrical systems are protected by a fuse. Electrical installation and wiring was and should be performed by a qualified professional.

Risks of hand injuries have to be considered while using the recycler. The stepper motor powering the recycler should be strong enough to break small plastic parts but too weak to cause injuries. The plastic waste input chamber has been designed to be "finger-proof" so it should not be possible to insert fingers in it. Nonetheless, it is recommended to handle the recycler with care and wear appropriate individual protection equipment.

The production of gaseous and fine particles emission have to be considered while using the recycler and the 3D-printer (Stephens et al. 2013). Incorrect use of the recycler such as inappropriate parameter settings and material input may lead to an overproduction of chemical compounds and particles released into the air which may be harmful. Therefore, it is recommended to wear breathing protection or to handle the system outside or in a well ventilated area.

In contrast to lithium polymer batteries, the $LiFePO_4$ battery is not considered as self-inflammable. However, short circuits and inappropriate damaging mechanical action could lead to exothermic chemical reactions. For this reason, the battery was additionally encapsulated in a housing and is not direct accessible. Furthermore, it is recommended not to touch the nozzles of the 3D printer and of the recycler in operation to avoid the risks of skin burns.

All in all, the system is largely self-explanatory and can be operated by untrained personnel after a short briefing. All plugs are reverse polarity protected and colour coded or labelled. In addition, the system comes with instructions for assembly and use.

Calibration

The 3D printer requires regular calibration, particularly the distance between the nozzle and the print bed. For this, refer to the Prusa i3 Hephestos instruction manuals.[7] The photovoltaic panels may require in-use calibration in order to find the best radiation angle. The CubeFactory does not include any automation regarded to optimal angle search. This has to be done manually during operation.

The optimal recycler temperature and spindle speed depend on the composition of the processed materials and their expected properties. The melting and solidification behaviour of plastics may be affected by a large number of parameters, among which the purity of the material.

The optimal recycling temperature depends on the glass-transition temperature and the melting point of the processed material. The glass-transition temperature is the point above which a brittle material becomes viscous and can undergo plastic transformations. The melting point marks the transition between solid and liquid states. The optimal extrusion temperature lays in a region below and close to the melting point. While the material must be clearly above the glass-transition temperature to yield enough viscosity, reaching and going beyond the melting point may lead to an excessive material volatility. Eventual additives in the material may exhaust, leading to potentially harmful gaseous emissions as well as to significant changes in the material properties. Excessive volatility may also lead to material losses. **Table 2** provides indicative thermic properties of three thermoplastics of general relevance in 3D-printing. Depending on the exact chemical composition of the materials and the presence of additives, these values may vary significantly. As a matter of comparison, tests performed on PET bottles from the dairy product "Muellermilch" yielded optimal results at 245°C.

The optimal temperature also depends on the extrusion speed, which in turn depends on the spindle speed and the inclination of the extruder screw thread. At high extrusion speed, there is a higher risk of producing irregular filament due to a partly molten material. At low extrusion speed, there is a higher risk of overheating and material losses.

Reliability

All subsystems, as well as the CubeFactory as a whole, were tested and adapted in iterative development cycles. A key challenge was the right balance of weight, sturdiness and usability. Although the first tests were quite successful, it became apparent with increasing use that some mechanical connections in the fixation of the subsystems in the housing loosen or failed. These had to be designed stronger to the detriment of the weight. However, since all subsystems were extensively tested in advance, the changes were often small or easy-to-implement.

The 3D printer was developed as an open-source machine in the RepRap project by Josef Průša in co-operation with the RepRap community and is generally regarded as a low-cost and reliable printer. Mechanical components consist to a large extent of commercially available standard components, which are available at low cost on the

Table 2: Thermic properties of ABS, PLA and PET.

Plastic type	Glass-transition temperature [°C]	Melting point [°C]
ABS	105–125	210–240
PLA	45–70	160–190
PET	70–80	250–260

market. Components that are specifically designed for the printer can be inexpensively manufactured with other 3D printers. The subsystem 3D Printer (Prusa i3) is technically mature and reliable.

The recycler, and especially the screw conveyor, geared motor and extruder frame, were designed with conservative security factors so they withstand the high mechanical stresses when extruding. Mechanical components and fits within the temperature-affected zone have been designed with respect to operating temperature and specific coefficient of thermal expansion. In addition, a double PEEK and air gap thermal barrier prevents the spread of heat between the sleeve heater and the 3D printed parts. These design features significantly increase the mechanical reliability of the system. Nonetheless, some failure modes may appear in operation: the shredder knifes may block due to too many or too hard plastic parts, the extruder screw may clog due to jamming of granules in front of the heating zone or connecting elements loosen due to the high process forces. In those cases, the system can usually be quickly made operational again by simple manipulations. All in all, the authors rate the reliability of the recycler as very good, considering that, despite previous experience in the construction of extruders, it is still version 1 of a new type of compact filament recycler.

Recycling quality

The recycler embedded in the CubeFactory2 belongs to a series of prototypes built by the authors and yielding similar output quality. These prototypes were tested by processing ABS casings, PET bottles, or PLA and ABS printing misfits (see some examples in **Figure 8**). Tests with ABS and PET proved to yield filament of satisfactory quality for modest 3D printing applications, whereas this quality obviously departs from those achieved by industrial recycled filament producers. Tests with PLA were not conclusive and yielded unusable brittle extrudate.

Since the recycler is not equipped with an extrusion puller to control the tension of the extrudate, the diameter of the produced filament may vary. This variance showed to be within the range of tolerance of common FFF 3D printers and does not impede the ability to print. Nonetheless, thicker or thinner spots lead to over- or under-extrusion and significantly reduce the regularity of the printing process. This irregularity can be reduced by using printing nozzle with higher diameter outlets (e.g. ø0.8 mm) providing a larger buffering capacity at low print speed. The resulting printing resolution loss can be balanced by aiming for larger prints. Also, while cooling, the filament may shrink in diameter, so it is recommended to use a slightly oversized nozzle, e.g. 2 mm nozzle for a 1.75 mm aimed filament diameter. Asymmetries in the material feed through the screw and nozzle also engender convolutions or waves in the produced filament. This can create asymmetrical friction in the 3D printer feeding system and can impede the 3D printing process through jamming. Because the Prusa i3 embeds a direct drive without a Bowden tube, it is relative tolerant to jamming produced by the irregular diameter and geometry of the recycled filament. Irregularities in the filament diameter and fracture frequency found to be less pronounced while extruding thick (ø2.85 mm) than thin (ø1.75 mm) filament. Waving and convolutions found to be less pronounced with thin filament due to higher cooling speed.

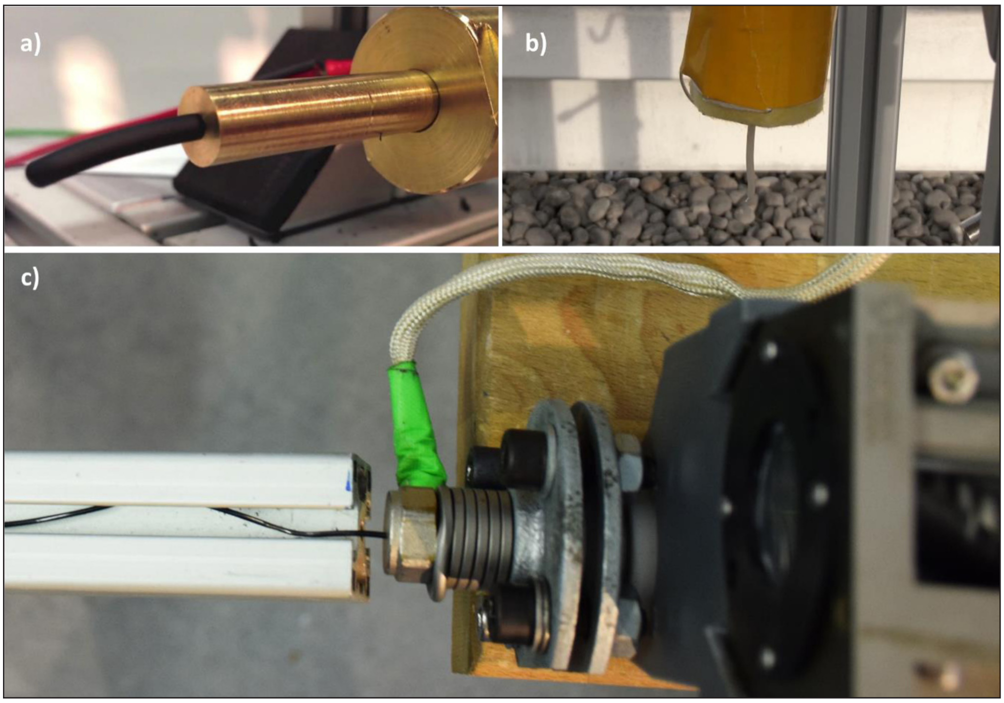

Figure 8: Example of extrusion jobs **a)** material: ABS misprints, device: Home Recycling Device extrusion diameter: 3 mm, extrusion temperature: 220°C, **b)** material PET bottles "Muellermilch", device: RecycleBin, extrusion diameter: 3 mm, extrusion temperature: 245°C, **c)** material: virgin ABS, device: CubeFactory2's embedded recycler, extrusion diameter: 2 mm, extrusion temperature 220°C.

Parallel experiments aiming to assess the deviation of mechanical properties between virgin and industrially recycled ABS and PET filament showed that some altered mechanical properties are to be expected (Tam et al. 2016). These results are summarized in **Table 3**. They have however been produced on a number of samples which is too small to claim any statistical relevance (5 samples per test, all from same filament spool). The quality of the filament produced by the recycler described here has only been assessed through practical printing tests. The execution of normed tests (i.e. ISO 527 and 178 for the determination of tensile and flexural properties) on a statistically significant number of extruded filaments and 3D print samples should be the object of further development efforts. It should be noted that the development of the recycler focused on compactness and functionality rather than optimal process quality.

The recycler does not contain any input material cleaning or sorting unit. Material fed into the recycler should be cleaned and dried prior to recycling since presence of foreign material and moisture affect the recycling process. It should also be paid attention that either pure materials are fed into the recycler or mixes of materials that are compatible for recycling. Users can refer to tables of material compatibility for recycling (e.g. Bishop 1999 p 401). There is no other specific pre-processing required than sorting and eventually cleaning, drying and cutting into pieces that fit in the hopper.

All material tests reported here have been made with pure, clean and dry materials. While in theory the recycler can take as input any pure or compatible mix of thermoplastic materials, this article only reports tests with ABS, PET and PLA. This article does not claim that the filaments produced by these tests reached a quality approaching or above industrial standards.

General advice for reaching a better output quality:

- Use a constant and reliable source of plastic waste (e.g. PET bottles used for packaging a given beverage) and for which parameters have previously been tested.
- Discard the first few extruded centimetres, since they may contain inconsistencies, bubbles or rests from previous extrusion jobs.
- Avoid recycling the same material too many times, since each recycling cycle degrades the material properties to some extent.
- Add some virgin plastic in the recycling mix (e.g. 20–30%) to improve the quality.

(3) Application

Consequently to the above mentioned limitations, filament produced by the recycler may be suitable for printing jobs of low requirements in terms of resolution, regularity, mechanical properties and surface appearance. In its current state of development, the CubeFactory2 is before all suitable for demonstration purposes. Further development could improve the suitability of this proof of concept for fabrication in areas of low infrastructure.

Education to sustainable manufacturing

The CubeFactory2 can support awareness on sustainable manufacturing and closed loop material cycles (see Roeder et al. 2017, and **Figure 9**). Pupils can be brought to concrete experience and be guided through reflective observation and abstract reconceptualization of these concepts exemplified by the portable mini-factory. By producing an object by themselves with the 3D-printer, they can learn which means of production (machines) and inputs (material, energy and information) this activity implies. Using the recycler, they can experience critical steps of recycling processes such as material identification, sorting and processing. By feeding the recycled filament into the 3D-printer, they can understand the concepts and the limits of circular economy. This illustrates through a practical example that waste is a valuable resource that can to a certain extent be put to new use. These are among others the learning effects which can be achieved through a guided use of the CubeFactory2 in teaching environment.

The current development status of the product makes it already suitable for this application. Due to its small size, the CubeFactory2 is easy to transport to schools. The quality of the printed filament is sufficient to make modest prints and therefore illustrate the concept of closed-loop material cycle and the limits of material recycling.

Value creation in areas with low infrastructure

As a long term vision, the CubeFactory2 could offer an off-grid portable production unit which is independent from any supply network. It could be used advantageously in areas where existing infrastructure has been damaged due to a natural catastrophe or where little infrastructure has been built, such as in remote or regions. Nonetheless, further work is required to bring the CubeFactory2 to a state of development which fully fits the requirements of this application, especially in terms of building cost and quality of recycled filament.

Table 3: Deviation of mechanical properties between virgin and industrially recycled ABS and PET (Tam et al. 2016).

	Tensile strength (MPa)	Nominal tensile strain (%)	Flexural strength (MPa)	Vickers hardness
ABS (virgin)	33.7	5.48	51.92	8.6
ABS (recycled)	24.7 (–27%)	5.29 (–3%)	42.61 (–18%)	7.8 (–9%)
PET (virgin)	65.9	5.02	95.98	16.2
PET (recycled)	35.4 (–46%)	2.87 (–43%)	52.31 (–46%)	10.4 (–36%)

Figure 9: The first version of the CubeFactory involved in school education.

Reuse potential and adaptability

The CubeFactory2 is no longer developed. Any replication and contribution to the improvement of the current version and its subsystems is welcomed and encouraged, as well as any dissemination activity towards the realisation of the use cases described above. For more information about the improvement potentials identified by the authors, please refer to section "future works".

(4) Build Details

Availability of materials and methods

Attention has been paid to build the CubeFactory with either standard, open source or self-developed components. However, some of the subsystems such as the casing and the PV modules are either bespoke parts or off-the-shelf components which are not open source. Their replicability is therefore limited. To build the open source 3D-Printer Prusa i3 Hephestos, refer to the related online documentation.[8] The bill of materials (BOM) of the recycler is available in the online documentation, accessible via the link provided in the section "hardware documentation and files location". It includes a systematic and hierarchic part nomenclature, references to standard part designations, the related part functions, quantities, unit prices and related CAD models. The complete set of CAD models for manufacturing the custom parts is also available in original format (SolidWorks) as well as in exchange formats (STEP and STL). Technical drawing with exploded views are also provided and give an overview of the required parts and their relative position. The cost of all parts for the built prototype is estimated to 6500€ in all. More than two thirds this cost is due to the bespoke power supply. Alternative solutions for the power supply could significantly reduce the cost to one third. All design documents are made freely accessible via an online repository under the link provided in the section "hardware documentation and files location".

Ease of build

Building the CubeFactory2 mainly requires mechanical, electronic and electrical assembly skills. The mechanical assembly does not require advanced skills. The electronic assembly may require a basic understanding or electrical engineering. The assembly of the photovoltaic energy system must be performed or supervised by a qualified electrical engineer.

Some parts of the recycler are custom built, especially the cutting unit. Simple parts have been 3D-printed or machined and more complex parts have been produced by selective laser melting (SLM). Producing these parts requires having access to corresponding 3D printer, CNC milling and SLM machines and to the corresponding qualified personal.

Operating software and peripherals

Operating the CubeFactory2 requires the ability to provide machine code (G-code) which is compatible with the Prusa i3 Hephestos 3D printer. This can be done using a computer based slicing application such as Cura,[9] which is available under an open source license. The generation of G-code by a slicing application further requires the ability to provide 3D-Models which can either be downloaded from dedicated Internet platforms or edited with CAD software such as FreeCAD,[10] which is available under an open source license.

Dependencies

The CubeFactory2 uses the 3D printer Prusa i3 Hephestos, whose hardware documentation licensed under GPL license (http://reprap.org/wiki/Prusa_i3_Hephestos). The Prusa i3 Hephestos can run with different pieces of firmware, among which the firmware Marlin (documentation https://reprap.org/wiki/Marlin, source code https://github.com/MarlinFirmware/Marlin). The CubeFactory2 does not contain any other software and is not dependent to any other external software or programming framework.

Hardware documentation and files location

Archive for hardware documentation, modifiable design files and build files

Name: https://github.com/CubeFactory2/cubefactory
Persistent identifier: https://doi.org/10.5281/zenodo.1194284
Licence: CC-BY-SA-4.0
Publisher: Bernd Muschard
Date published: 03/06/2016 to 20/08/2017 (first/last commits)

(5) Discussion

Conclusions

In this hardware meta-paper, we described an off-grid and portable mini-factory referred to as the CubeFactory2. Its distinctive features are compactness and autonomy. The whole system is embodied in a flight case measuring one sixth of a cubic meter and weighs less than 32 kg. It can potentially run indefinitely provided the on-site presence of sufficient thermoplastic waste and solar energy. It is designed with two main uses cases in mind, namely off-grid production and education to closed-loop production cycles, both of them illustrating the concept of sustainable manufacturing. This paper described the overall system design and those of the four main subs-systems, namely the recycler, the 3D-printer, the energy supply and the casing. It provides design information complementing the open source documentation published in a publicly accessible online repository with the aim of fostering replicability and further development.

Future Work

In its current form, the CubeFactory2 remains a proof of concept and would benefit undergoing further development to reach a market-ready state. Further efforts could be undertaken to cut the costs, miniaturize the subsystems in order to reduce both volume and weight, or increase the process quality of the recycler. Particular improvement potentials are:

- Redesign the photovoltaic energy supply system with inexpensive off-the-shelf components.
- Use an open source flight case or design a new one.
- Reduce electrical risks by removing the 240V inverter and the corresponding circuit supplying the 3D-printer with alternative current. Given minor modifications, the 12V DC current required by the 3D-printer could be provided directly from the energy supply system without requiring conversion. These modifications would increase energy efficiency, reduce manufacturing and assembly costs.
- Enhance the flexibility of energy intake, allowing the system to be supplied by other energy sources such as wind or water.
- Reducing the design complexity of the shredder to avoid the use of advanced manufacturing processes such as Selective Laser Melting.
- Perform systematic tests to characterize the quality of the extrudate yielded by the recycler, e.g. compare the mechanical properties of parts printed out of virgin and recycled materials, characterize the regularity of the yielded filament, and identify optimal extrusion conditions.
- Allow a simpler mechanism to switch the motor between the extruder and shredder position. In the current version, the motor needs to be unscrewed from one position to be screwed to the other one. The time to process this operation lies below 5 minutes, but could be reduced by a mechanism that is easier to operate while yielding similar fixation strength.
- Embed best practices of recycler design benchmarked from other recyclers that have been developed and put on the market in the meantime. Desktop filament recycling is a relatively new but rapidly developing branch.
- Add extrusion pulling, spooling and filament cooling functions in order to improve the regularity of the extruded filament.

Notes

1 https://preciousplastic.com/en/videos/build/extrusion.html.
2 https://felfil.com.
3 https://opensource.org/osd.
4 http://certificate.oshwa.org/.
5 https://vimeo.com/126693055.
6 Three modules of 1.015 m^2 each (1.45 m × 0.7 m), with a summative surface of 3.045 m^2.
7 http://reprap.org/wiki/Prusa_i3_Hephestos.
8 http://reprap.org/wiki/Prusa_i3_Hephestos.
9 https://en.wikipedia.org/wiki/Cura_(software).
10 https://www.freecadweb.org/.

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Reviewers

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The discussion between the authors and the reviewers is reproduced in the supplementary material, where the reviewers are referred to as reviewer 2,3,4,1 respectively in the above order.

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Competing Interests
The authors have no competing interests to declare.

Author Contributions
Bernd Muschard participated to the development of the first CubeFactory in 2012 and led the development of the CubeFactory2 from 2015 to 2017. He participated actively to the development of both prototypes, led the open source documentation and publication performed in 2017 and contributed to the present article. Jérémy Bonvoisin advised the open source documentation and publication performed in 2017 and contributed to the writing of the present manuscript.

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